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RESEARCH MEMORANDUM

FREE-JET ALTITUDE INVESTIGATION OF A 20-INCH RAM-JET COMBUSTOR WITH A RICH INNER ZONE OF COMBUSTION FOR IMPROVED LOW-TEMPERATURE-RATIO OPERATION

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation of the altitude performance of a 20-inch-diameter high-temperature-ratio ram-jet combustor which had been redesigned to provide good combustor efficiency over a wide range of temperature ratios was conducted at zero angle of attack in a free-jet facility at a Mach number of 3.0. Most of the investigation was for operation at a simulated altitude of about 70,400 feet. Configurations investigated incorporated a cylindrical control sleeve which confined the injected fuel at lean over-all fuel-air ratios to about 40 percent of the engine air flow, thus maintaining an optimum fuel-air mixture over a portion of the flame holder when the over-all fuel-air ratio was about 0.015 to 0.02. Exhaust nozzles of 45 and 55 percent of the combustion-chamber area were used in combination with combustion-chamber lengths of 48 and 77 inches.

Whereas the original engine configuration, which contained no control sleeve, had a lean limit of operation at a fuel-air ratio of about 0.03, the configurations with the control sleeve reported herein operated well at a fuel-air ratio of 0.015 or lower. The inner combustion zone had peak combustor efficiencies from 0.80 to 0.88 at a fuel-air ratio of about 0.02 for the various configurations. With both inner and outer zones burning, peak combustor efficiency was 0.88 to 0.92 at a fuel-air ratio of 0.045 to 0.05, which was essentially the same as for the original engine configuration. The control sleeve caused only a slight increase in the burner total-pressure loss. Thus, possibilities seem good for the development of an engine to satisfy the requirements for a long-range missile or for tactical missiles requiring variable thrust for maneuvering (i.e., good combustion efficiency over a wide range of temperature ratios).

INTRODUCTION

Theoretical analysis has shown that hydrocarbon-burning ram-jet engines which could power a long-range missile at cruise conditions must

operate with good combustion efficiency at a relatively low fuel-air ratio. Analysis also indicates that on an over-all gross-weight basis (including rocket boost), an optimum, long-range, ram-jet-missile flight plan might include a relatively moderate external boost to some flight Mach number and altitude below cruise conditions and would utilize the missile ram-jet engines to accelerate and climb to the cruise altitude and flight Mach number. Such a flight plan would call for an engine with a variable-geometry inlet and exit and with a combustion chamber capable of operating efficiently over a wide range of temperature ratios and pressures. High temperature ratios (near stoichiometric fuel-air ratio) would be required during the accelerating phase of the flight, and low temperature ratios (fuel-air ratios of 0.02 to 0.03), for the long-range cruise portion of flight. A combustion chamber which could operate over a wide range of temperature ratios might also be needed for a tactical missile requiring variable thrust for maneuvering.

A collection of experimental ram-jet data compiled from various unrelated sources by the Lewis laboratory staff in early 1952 showed that there was not available, at that time, performance data for a ram-jet combustor that could operate with good combustion efficiency (e.g., 90 percent or above) over a wide range of temperature ratios. This collection of data indicated, however, that there were promising design techniques in the ram-jet-combustor field which, if properly developed, might make it possible to incorporate the desired operating characteristics in a single ram-jet engine. Accordingly, a program was initiated in March 1952, at the Lewis laboratory for an intensive and systematic research program aimed at the development of a full-scale ram-jet engine suitable for long-range application.

One method that has been proposed to maintain high combustion efficiency at low over-all fuel-air ratios consists of confining the injected fuel to a portion of the combustion-chamber air in such a way that an optimum local fuel-air ratio is maintained over a portion of the flame-holding system. The use of such a method is reported in reference 1, in which it is shown that, by properly controlling the fuel-air mixing process, large gains in combustion efficiency at low over-all fuel-air ratios can be obtained. This method of confining the fuel-air mixture was applied in the part of the development program which is reported herein.

The data presented herein were obtained by operation of a 20-inch-diameter ram-jet engine installed at zero angle of attack in a free-jet test facility. The nominal Mach number of the jet was 3.0, and the range of simulated altitudes in the jet was from 60,500 to 70,400 feet. The inlet total temperature was held constant at 1100° R, which is the standard total temperature for a flight Mach number of 3.0 above the tropopause. Performance at the lower inlet pressures and temperatures which might be encountered in some long-range missile flight plans was not investigated in the phase of the program reported herein. This engine had been originally designed for high-temperature-ratio operation, and the performance of this engine is reported in reference 2, where it is shown that the combustor efficiency decreased rapidly below a fuel-air

ratio of about 0.04. The control-sleeve method of reference 1 was applied to this engine with the objective of obtaining high combustor efficiency at a fuel-air ratio of about 0.02 without compromising the performance at higher fuel-air ratios. The control sleeve was designed to capture about 40 percent of the incoming air flow so that, at overall fuel-air ratios of about 0.02, a local fuel-air ratio close to 0.05 (the region of peak efficiency conditions for the original configuration reported in ref. 2) could be maintained at the flame-holding elements.
2720 In an attempt to improve the performance of the configuration with the control sleeve at a lean fuel-air ratio, the effects of exhaust-nozzle size and combustion-chamber length as well as minor modifications to the control sleeve and pilot were investigated.

APPARATUS

Test Facility

The ram-jet engine was mounted in a free-jet test facility which is shown schematically in figure 1. Air entered the facility through a combustion-type preheater and a surge tank and was then expanded through a converging-diverging nozzle to the design Mach number of 3.0 ahead of the engine inlet. A complete description of this test facility and its operation is reported in reference 3.

Engine

A diagrammatic sketch of the 20-inch-diameter ram-jet engine is shown in figure 2. The inlet diffuser was of the double-cone annular type which utilizes two oblique shocks and one normal shock. The subsonic diffuser portion was divided into three channels by the centerbody supports which extended downstream to the end of the inner body. The flame holder and pilot burner were built integrally, and the pilot burner was mounted on the blunt end of the inner body. The pilot burner was 6 inches in diameter and 8 inches long. Louvers near the upstream end of the pilot burner provided air for pilot combustion. Three gutters, which were 3 inches wide at the open end, extended radially from the downstream end of the pilot burner. These gutters formed channels 4.4 inches deep and were mounted on the blunt ends of the inner-body supports. Two circular V-gutters 1 inch wide and with a 60° included gutter angle interconnected the radial gutters at radii of 6.0 and 8.5 inches. Total blockage of the flame holder was 55 percent of the combustion-chamber area. The engine fuel was injected through 27 nozzles which were located 17 inches upstream of the flame holder and which sprayed in a downstream direction. The nozzles were located in two concentric circular manifolds, each of which was divided into three segments because of the inner-body supports. Each outer manifold segment was

equipped with five equally spaced fuel nozzles and each inner segment had four equally spaced nozzles. In order to simplify maintenance, fixed-area fuel spray nozzles were substituted for the original pintle-type nozzles which were used in the investigation reported in reference 2. Performance with the two types of nozzles was virtually the same. A single fuel nozzle supplied fuel to the pilot burner. Ignition of the pilot burner was accomplished by means of an igniter which extended radially into the pilot burner and which burned an electrically ignited mixture of propane and air.

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The engine was equipped with a contoured convergent exhaust nozzle which had a minimum area equal to 55 percent of the combustion-chamber area. A more complete description of this engine and its unmodified performance is given in reference 2.

Configurations

Seven configurations were investigated in the evaluation of the inner-control-sleeve technique as applied to the 20-inch ram-jet engine. The pertinent features of each are summarized in the following table, and each is briefly described in the succeeding paragraphs:

Configuration number	Control sleeve	Pilot	Combustion-chamber length, in.	Exhaust-nozzle area, percent of combustion-chamber area
1	None	Original with louvers	48	55
2	Extended from fuel nozzles to flame holder			
3	Extended 8 in. downstream of flame holder			
4		Louvers closed and holes drilled near downstream end		
5				45
6			77	55
7				45

Configuration 1. - Configuration 1, which is described in the preceding section and is shown diagrammatically in figure 2, was used in determining the engine performance presented in reference 2 and is included to form a basis of comparison for the modified configurations. The combustion-chamber length was 48 inches, and the exhaust-nozzle area was 55 percent of the combustion-chamber area.

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Configuration 2. - For configuration 2 a cylindrical control sleeve was installed which extended from between the fuel-injection manifolds downstream to the plane of the annular flame-holding gutters (fig. 3). The control sleeve was designed to capture approximately 40 percent of the engine air flow and to confine all the fuel injected by the inner manifold within the control sleeve, thus making it possible to maintain a rich local fuel-air mixture at the flame holder while the engine was operating at a lean over-all fuel-air ratio.

Configuration 3. - Configuration 3 incorporated a downstream addition to the control sleeve which extended 8 inches beyond the flame holder into the combustion chamber (fig. 4). The control sleeve was extended to prevent the possibility of premature quenching of the flame seated on the inner V-gutter by the air from the outer zone.

Configuration 4. - An attempt was made to increase the inner-zone combustor efficiency with configuration 4 by providing stronger piloting. Fifteen 1/2-inch-diameter holes in the side of the pilot burner were substituted for the original air-entry louvers at the rear of the pilot burner, thereby enlarging the recirculation zone and increasing the pilot air flow. The control sleeve and its extension were retained in configuration 4. The new holes and the blocked-off louvers may be seen in figure 4.

Configurations 5, 6, and 7. - Configurations 5, 6, and 7 incorporated modifications to determine the effect of inlet velocity and burner length upon combustor performance. Configuration 5 was the same as configuration 4 with the exception of the exhaust nozzle which had an area of 45 percent of the combustion-chamber area. Configuration 6 was the same as configuration 4 except that a 29-inch extension was added to the combustion chamber. Configuration 7 was the same as configuration 6 except for the exhaust nozzle which was 55 percent of the combustion-chamber area.

Instrumentation

The locations of temperature and pressure measurements at the various instrument stations are shown in figures 1 and 2. The total pressure and temperature were measured in the surge tank ahead of the supersonic nozzle (fig. 1) and were used in determining engine ambient

conditions. A survey of total and static pressures was made in the engine at a station near the downstream end of the subsonic diffuser (fig. 2) and the results were used in calculating the burner total-pressure ratio and the combustion-chamber-inlet Mach number. A water-cooled rake located just upstream of the exhaust nozzle was employed to measure the total pressure in the combustion chamber for use in air-flow and efficiency calculations. The fuel flow to both the preheater and the engine was measured by calibrated rotameters. Air flow to the preheater was measured with an A.S.M.E. flat-plate orifice.

PROCEDURE

Simulated Flight Conditions

A flow Mach number of approximately 3.0 was obtained ahead of the engine diffuser inlet by means of a convergent-divergent nozzle (ref. 3). The total temperature of the air entering the surge tank was raised to 1100° R by a combustion-type preheater to simulate the standard total temperature for a flight Mach number of 3.0 at altitudes above the tropopause. The total pressure in the surge tank was varied to simulate altitudes of about 60,500 to 70,400 feet in the supersonic jet ahead of the engine diffuser. The engine, however, by virtue of its inlet and exit geometry, operated supercritically for all fuel-air ratios. Therefore, the combustion-chamber pressures were somewhat lower for these simulated altitudes than are obtainable in practice with a better matching of inlet and exit geometry.

Method of Engine Operation

After full supersonic flow had been established in the supersonic nozzle, the throttling valve (fig. 1) was partially closed to raise the pressure level and reduce the velocities in the engine sufficiently to permit ignition of the pilot burner and the inner zone of the main burner. When burning had been established, the throttling valve was opened and the engine exhaust nozzle choked. Fuel flow to the inner zone was varied to cover the range of operation from lean to rich blow-out (or to the pumping capacity of the inner-zone fuel system). The inner-zone fuel flow was then held at the optimum value (peak combustor efficiency) as fuel flow to the outer zone was initiated and varied to obtain engine performance at high fuel-air ratios. The fuel used in the evaluation of configuration 1 was MIL-F-5624 grade JP-3. For all other configurations the fuel used was MIL-F-5624A grade JP-4.

Calculations

The engine fuel-air ratio was calculated as the ratio of engine fuel flow to the unburned-air flow entering the engine. Combustor

efficiency was taken as the ratio of ideal to actual fuel-air ratio, where the ideal fuel-air ratio was that necessary to obtain, in an ideal combustion process, the total pressure which was measured at the exit of the engine combustion chamber. The symbols and the methods used to calculate engine air flow, fuel-air ratio, combustor efficiency, and combustion-chamber-inlet Mach number are outlined in appendixes A and B, respectively.

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RESULTS AND DISCUSSION

In order to establish a datum with which the performance of the various control-sleeve configurations could be compared, the performance of the original engine configuration reported in reference 2, and herein referred to as configuration 1, is presented in figure 5. Combustor efficiency (fig. 5(a)), burner total-pressure ratio (fig. 5(b)), combustion-chamber total pressure (fig. 5(c)), and combustion-chamber-inlet Mach number (fig. 5(d)) are plotted as functions of fuel-air ratio for several altitudes. Of principal importance with reference to this investigation are the curves of combustor efficiency (fig. 5(a)). Peak efficiency of approximately 0.90 occurred at a fuel-air ratio of about 0.042 for a range of altitudes from 60,500 to 66,500 feet. A gradual decrease in efficiency occurred as the fuel-air ratio was increased beyond the value for peak efficiency. The efficiency decreased very rapidly, however, as the fuel-air ratio was reduced from the peak-efficiency value until lean blow-out was encountered at a fuel-air ratio of about 0.03. This characteristic of poor combustor efficiency at fuel-air ratios lower than about 0.04 is typical of a ram jet designed for high-temperature-ratio operation; and, in accordance with the objectives outlined in the INTRODUCTION, it was this trend which was to be eliminated, insofar as possible, by using the control sleeve.

Effect of Control Sleeve and Control-Sleeve Extension

Configuration 2. - In configuration 2 the principles of localizing fuel-air ratio which are set forth in reference 1 were applied in an attempt to obtain high combustor efficiencies at low fuel-air ratios. Performance for this configuration is presented in figure 6, where combustor efficiency, burner total-pressure ratio, combustion-chamber total pressure, and combustion-chamber-inlet Mach number are plotted as functions of fuel-air ratio for altitudes of 60,500 and 70,400 feet. The range of engine operation was greatly extended in the region of lean fuel-air ratios, as can be seen in figure 6(a) by comparing the performance of the inner zone alone with the typical performance of configuration 1. The peak combustor efficiency for the inner zone alone was about 0.78 at a fuel-air ratio near 0.02 for both altitudes. The combustor efficiency decreased slightly as the inner-zone fuel-air ratio was increased from 0.02 to 0.04. Operation at a fuel-air ratio leaner than 0.02 resulted in lean blow-out for the higher altitude and a very rapid decrease in combustor efficiency for the lower altitude. The control

sleeve had little effect upon combustor efficiency above a fuel-air ratio of 0.05 with both inner and outer zones burning.

As previously stated, different fuels were used in the evaluation of configurations 1 and 2 (MIL-F-5624 grade JP-3 for configuration 1 and MIL-F-5624A grade JP-4 for configuration 2). It is believed, however, that the change in fuel type during this program had little effect on combustor performance at the inlet pressure and temperature conditions of the investigation. In any event, the improved performance of configuration 2 at fuel-air ratios leaner than 0.035 could not be attributed to the slight differences in fuel used.

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The burner total-pressure ratio (fig. 6(b)) was only 1 or 2 percent lower than for configuration 1 (fig. 5(b)). Combustion-chamber total pressure and combustion-chamber-inlet Mach number for configuration 2 are shown in figures 6(c) and 6(d), respectively. It may be seen from figure 6 that altitude had no significant effect upon burner performance within the range for which data were obtained. This insensitivity to altitude was also observed for other configurations. For simplicity, therefore, only the performance data for one altitude (approximately 70,400 ft) are presented in the subsequent discussion of configurations 3 to 7.

Configuration 3. - Whereas the control sleeve of configuration 2 extended the lean range of operation to a fuel-air ratio of 0.02 before a marked decrease in efficiency or blow-out occurred, the level of peak combustor efficiency with inner-zone injection alone was about 10 points lower than that with injection in both zones. It was felt that approximately equal efficiencies should be obtainable with both methods of injection. Therefore, in order to eliminate the possibility that the low inner-zone combustor efficiency of configuration 2 might be caused by premature quenching of the inner-zone flame by the air of the outer zone, the control sleeve was extended 8 inches beyond the plane of the flame holder. The performance of this configuration is presented in figure 7. Figure 7(a) shows that the maximum combustor efficiency of the inner zone was about the same as for configuration 2, but occurred at a leaner fuel-air ratio of approximately 0.015. Configuration 3, therefore, did not raise the peak inner-zone combustor efficiency to the desired value. The sleeve extension caused a rather rapid decrease in efficiency as the fuel-air ratio of the inner zone was increased from the point of maximum efficiency. This was probably due to the confining of the over-rich mixture from the inner zone too far downstream in the combustion chamber to permit mixing and burning with the air from the outer zone. The control-sleeve extension also isolated the outer-zone flame-holding gutters from the piloting system. This prevented flame seating on the outer-zone gutters for lean mixtures in the outer zone. The result was a rapid decrease in efficiency when operating with both zones as the fuel-air ratio was decreased from the point of maximum efficiency. Thus the control-sleeve extension caused a large region of low efficiency in the range of fuel-air ratios between 0.02 and 0.05 when operating with both zones. The efficiency peak for operation with both zones was at a fuel-air ratio of 0.05 (leaner than for configuration 2), and the maximum efficiency of 85 percent was slightly lower

than for the previous configurations. This lower peak efficiency for operation with both zones resulted from holding the inner-zone fuel flow at a value corresponding to an over-all fuel-air ratio of 0.025 rather than the optimum of 0.015. Discussion of a subsequent figure shows the important effect of inner-zone fuel flow upon peak over-all efficiency.

In figure 7(b) the burner total-pressure ratio is shown to be about 1 percent lower with the control-sleeve extension than it was for configuration 2.

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Effect of Pilot-Burner Modifications - Configuration 4

The sleeve extension of configuration 3 was observed to have no effect on peak combustor efficiency in the lean range of fuel-air ratios. In a further effort to raise the peak efficiency in the lean range of fuel-air ratios, modifications to the pilot were made. It was felt that an increase of pilot-burner heat release might have a beneficial effect on mainstream burning. In configuration 4, therefore, the original upstream louvers in the pilot burner were closed and air admission holes were drilled approximately 6 inches downstream of the pilot-burner mounting face.

Typical inner-zone performance of this configuration (for one pilot fuel flow) is shown in figure 8 and is essentially the same as the performance of configuration 3. Any consistent trends due to the changes made in the pilot burner or variations in the pilot-burner fuel flow were not apparent; either there were none, or they were obscured by the spread of data points. In any event, the effect could not have been more than 2 or 3 points on the peak efficiency.

Effect of Combustion-Chamber Length and Inlet Velocity

Because the control-sleeve extension and pilot-burner modifications did not raise the peak efficiency of inner-zone operation, it was decided to decrease the combustion-chamber-inlet velocity and to increase the combustion-chamber length to see if any improvements in efficiency could be obtained by these methods.

<u>Configuration 5</u>. - For configuration 5 the exhaust-nozzle size was reduced from 55 to 45 percent of the combustion-chamber area. This decreased the combustion-chamber velocities approximately 20 percent and resulted in a corresponding increase in pressures for a given altitude. The performance of configuration 5 is presented in figure 9. Figure 9(a) shows that the peak efficiencies were not noticeably changed from those of previous configurations. The rich blow-out point for the inner zone was extended from a fuel-air ratio of about 0.04 to about 0.05 because

of the more favorable conditions of pressure and velocity at the flame holder. The combustor efficiency curve with fuel injection in both zones still showed a region of low efficiency around a fuel-air ratio of 0.035 due to the control-sleeve extension. The burner total-pressure ratio shown in figure 9(b) was about 2 or 3 points higher compared with configurations 3 and 4 because of the lower flame-holder pressure drop at the lower velocities. The combustion-chamber-inlet Mach number (fig. 9(d)) decreased about 17 percent from the values of figure 6(d).

<u>Configuration 6</u>. - Configuration 6 incorporated a combustion- 2720
chamber extension which increased the combustion-chamber length by 60 percent. The 55-percent exhaust nozzle was used for this configuration. The performance for configuration 6 is shown in figure 10. The maximum combustor efficiency for the inner zone was 0.88 at a fuel-air ratio of 0.015 (fig. 10(a)). This was an increase of 8 points over previous configurations. Operation at fuel-air ratios leaner than 0.015 and richer than 0.04 for the inner zone was purposely not attempted for configuration 6 because of operational difficulty with the propane igniter which would have prevented reignition of the engine in the event of a blow-out. The decrease in combustor efficiency on the rich side of the maximum efficiency point for the inner zone was not as pronounced with the long combustion chamber as it was with the short chamber. This was probably due to the fact that the increased length provided for better mixing of the over-rich mixture of gases from the inner zone with the air from the outer zone, thus permitting more complete combustion. For burning with both zones the peak efficiency was increased about 5 points over previous configurations to 0.92 at a fuel-air ratio of 0.045. Thus it is apparent that the added combustion-chamber length had a beneficial effect upon the combustor efficiency.

<u>Configuration 7</u>. - For configuration 7 the additional combustion-chamber length was retained, and the 45-percent exhaust nozzle was again used to determine the effect of combustion-chamber-inlet velocity. The performance of configuration 7 is presented in figure 11. The inner-zone peak efficiency (fig. 11(a)) was slightly lower for this configuration than for configuration 6. The peak efficiency for fuel injection in both zones was unchanged. Thus, as for configuration 5, the decrease in combustion-chamber-inlet velocity did not increase the peak combustor efficiencies. The rich limit of operation of the inner zone alone was extended from a fuel-air ratio of 0.05 (fig. 9(a)) to above 0.0575 by the added combustion-chamber length. Operation at fuel-air ratios above 0.0575 was not possible with the inner zone because of the limitations of the fuel supply system. The effect of changes in inner-zone fuel flow when burning with both zones is shown by figure 11(a), where the spread of efficiency with variations in inner-zone fuel flow was as large as 20 points (at an over-all fuel-air ratio of 0.045). The key in figure 11 gives the inner-zone fuel pressure, which was held constant during burning with both zones, and also the corresponding fuel-air ratios

for these pressures when the inner zone was burning alone. The three curves of combined inner- and outer-zone burning appear to be similar, except that the peaks were shifted to richer fuel-air ratios and lower combustor efficiencies as the inner-zone fuel rate was increased. This indicates that the local combustion performance of the outer zone is relatively independent of the local inner-zone fuel rate and that changes in the combined performance of both zones as the inner-zone fuel rate is
2720 varied are primarily due to the changes of inner-zone performance. Thus, the best performance with both zones was obtained when the inner-zone fuel flow was held at a value which gave the best efficiency when the inner zone was operated alone.

CONCLUDING REMARKS

The insertion of a fuel-mixture control sleeve provided an optimum local fuel-air ratio over a portion of the flame-holding system and permitted operation at reasonably high combustor efficiency at low fuel-air ratios without compromising the performance for high-fuel-air-ratio operation. Such combustor characteristics would satisfy the requirements of long-range missiles needing full engine power during boost and climb, and economical low-fuel-air-ratio operation during cruise.

Addition of the control sleeve, which caused only a slight increase in the burner total-pressure loss, extended the lean limit of operation from a fuel-air ratio of 0.03 for the configuration with no sleeve to fuel-air ratios of slightly less than 0.015 for the modified configurations. The peak inner-zone combustor efficiencies for the modified configurations were from 0.80 to 0.88 at a fuel-air ratio of about 0.02 and simulated altitudes of 60,500 to 70,400 feet at a flight Mach number of 3.0. The peak over-all combustor efficiencies were from 0.88 to 0.92 at a fuel-air ratio of 0.045 to 0.05 for the modified configurations, which were essentially the same as for the configuration with no control sleeve.

A decrease in combustion-chamber-inlet velocity of approximately 20 percent had no significant effect upon peak combustor efficiencies. In contrast, an increase of 60 percent in combustion-chamber length increased the peak combustor efficiency of the inner zone by as much as 8 points and increased the peak efficiency for burning in both zones by 5 points.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
B	fraction of supersonic jet flow entering engine inlet
C_d	discharge coefficient of engine exhaust nozzle
f/a	engine fuel-air ratio
$(f/a)'$	ideal fuel-air ratio
$(f/a)_p$	fuel-air ratio of preheater
$(f/a)_s$	stoichiometric fuel-air ratio
g	acceleration due to gravity, ft/sec^2
M	Mach number
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
R	gas constant, ft-lb/(lb)($^{\circ}$R)
T	total temperature, $^{\circ}$R
V	velocity, ft/sec
W	engine inlet-air flow, lb/sec (containing preheater products of combustion)
W_a	air flow to preheater, lb/sec
$W_{f,e}$	fuel flow to engine, lb/sec
$W_{f,p}$	fuel flow to preheater, lb/sec
W_u	unburned-air flow entering engine, lb/sec
γ	ratio of specific heats

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η combustor efficiency

ρ density, lb/cu ft

Subscripts:

0 free stream

1 lip of inlet cowl

2 subsonic-diffuser exit

2' conditions at station 2 adjusted to combustion-chamber area

3 plane of flame holder

4 exhaust-nozzle inlet

5 exhaust-nozzle minimum area

c cold (i.e., engine not burning)

h hot (i.e., engine burning)

APPENDIX B

METHODS OF CALCULATION

Engine inlet-air flow. - The engine exhaust nozzle served as a convenient metering orifice for determining the rate of flow of air through the engine for nonburning conditions. Inasmuch as the diffuser was operating supercritically at all times, the inlet-air flow, at a given altitude, was the same for burning and nonburning conditions. The engine inlet-air flow was calculated from the mass-flow equation

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$$W = \rho_{5,c} C_{d,c} A_5 V_{5,c} \tag{1}$$

This was expressed as

$$W = F(P_{5,c}, C_{d,c}, A_5, T_{5,c}, M_{5,c}, \gamma, g, R) \tag{2}$$

where $P_{5,c}$ and $T_{5,c}$ were assumed equal to $P_{4,c}$ and T_0, respectively. The exhaust nozzle was choked so that $M_{5,c}$ was equal to 1. The exhaust-nozzle discharge coefficient $C_{d,c}$ was assumed to be 0.985. Leakage through the engine flanges was assumed to be negligible.

Engine fuel-air ratio. - The engine fuel-air ratio was defined as the ratio of the engine fuel flow to the unburned air passing through the engine inlet. Leaving the preheater was a gas which had a fuel-air ratio of

$$(f/a)_p = \frac{W_{f,p}}{W_a} \tag{3}$$

It was found that the preheater combustion efficiency was nearly 100 percent. The ratio B of the engine inlet-air flow to the supersonic nozzle flow was constant for all inlet pressures. The unburned air entering the engine was then

$$W_u = BW_a\left[1 - \frac{(f/a)_p}{(f/a)_s}\right] \tag{4}$$

This is different from W, which includes preheater products of combustion. The engine fuel-air ratio was then

$$f/a = \frac{W_{f,e}}{BW_a\left[1 - \frac{(f/a)_p}{(f/a)_s}\right]} \tag{5}$$

Because it was more convenient to measure the engine inlet-air flow W than BW_a, use was made of the following relation:

$$W = B(W_a + W_{f,p}) = BW_a\left[1 + (f/a)_p\right] \tag{6}$$

Rearranging gives

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$$BW_a = \frac{W}{\left[1 + (f/a)_p\right]} \tag{7}$$

Substitution of equation (7) in equation (5) gives

$$f/a = \frac{W_{f,e}}{W}\left[\frac{1 + (f/a)_p}{1 - \frac{(f/a)_p}{(f/a)_s}}\right] \tag{8}$$

Combustor efficiency. - The combustor efficiency η was defined as

$$\eta = (f/a)'/f/a \tag{9}$$

where f/a is given by equation (8) and $(f/a)'$ is the ideal fuel-air ratio which would have produced the same burner pressure P_4 as was measured for the burning conditions under consideration. Thus, the efficiency was related only to burner pressure, obviating the direct measurement of the high combustion-chamber temperatures.

The determination of $(f/a)'$ was implemented in the following way. Because the engine inlet diffuser operated supercritically at all times, the entering-air flow at a given altitude was the same for the nonburning and burning conditions and could be expressed as

$$W = \rho_{5,c}C_{d,c}A_5V_{5,c} = \frac{\rho_{5,h}C_{d,h}A_5V_{5,h}}{1+\frac{W_{f,e}}{W}} \tag{10}$$

By use of the equation of state and by converting static pressure and temperature to total values and velocity to Mach number, equation (10) may be expressed as

$$P_{5,h} = \frac{W\left(1 + \frac{W_{f,e}}{W}\right)}{C_{d,h}A_5M_{5,h}}\sqrt{\frac{R_hT_{5,h}}{\gamma_h g}}\left(1 + \frac{\gamma_h - 1}{2}M_{5,h}^2\right)^{\frac{\gamma_h+1}{2(\gamma_h-1)}} \tag{11}$$

or

$$P_{5,c} = \frac{W}{C_{d,c}A_5M_{5,c}}\sqrt{\frac{R_cT_{5,c}}{\gamma_c g}}\left(1 + \frac{\gamma_c - 1}{2}M_{5,c}{}^2\right)^{\frac{\gamma_c+1}{2(\gamma_c-1)}} \tag{12}$$

Dividing equation (11) by equation (12), assuming that

$$P_{5,c} = P_{4,c} \tag{13}$$ 2720

$$P_{5,h} = P_{4,h} \tag{14}$$

$$T_{5,c} = T_{4,c} = T_0 \tag{15}$$

$$T_{5,h} = T_{4,h} \tag{16}$$

$$C_{d,h} = C_{d,c} \tag{17}$$

and noting that

$$M_{5,c} = M_{5,h} = 1 \tag{18}$$

the following equation is obtained

$$\frac{P_{4,h}}{P_{4,c}} = \sqrt{\frac{T_{4,h}}{T_0}}\left(1 + \frac{W_{f,e}}{W}\right)\sqrt{\frac{\left[\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{R}{\gamma}\right)\right]_h}{\left[\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{R}{\gamma}\right)\right]_c}} \tag{19}$$

Equation (19) was evaluated for various engine fuel-air ratios by using theoretical combustion charts, which included effects of dissociation, to find $T_{4,h}$. These data were then plotted as $(f/a)'$ against $P_{4,h}/P_{4,c}$. By referring to this plot, the theoretical fuel-air ratio $(f/a)'$ could be obtained for each value of $P_{4,h}/P_{4,c}$ measured in the engine combustion chamber.

The combustor efficiency as defined above is not a chemical combustion efficiency such as a heat-balance or enthalpy-rise method would indicate. The combustor efficiency based on total-pressure measurement

is, however, more representative of over-all engine performance, in view of the fact that it indicates how effectively the fuel is being used to provide thrust potential rather than how completely the fuel is being burned.

<u>Combustion-chamber-inlet Mach number</u>. - The combustion-chamber-inlet Mach number was calculated by using the engine inlet-air flow W, the static pressure measured in the engine inlet diffuser p_2, the 2720 ambient total temperature T_0, and the maximum area of the combustion chamber (314.2 sq in.).

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2. Smolak, George R., and Wentworth, Carl B.: Altitude Performance of a 20-Inch-Diameter Ram-Jet Engine Investigated in a Free-Jet Facility at Mach Number 3.0. NACA RM E52K24, 1953.

3. Wentworth, Carl B., Hurrell, Herbert G., and Nakanishi, Shigeo: Evaluation of Operating Characteristics of a Supersonic Free-Jet Facility for Full-Scale Ram-Jet Investigations. NACA RM E52I08, 1952.

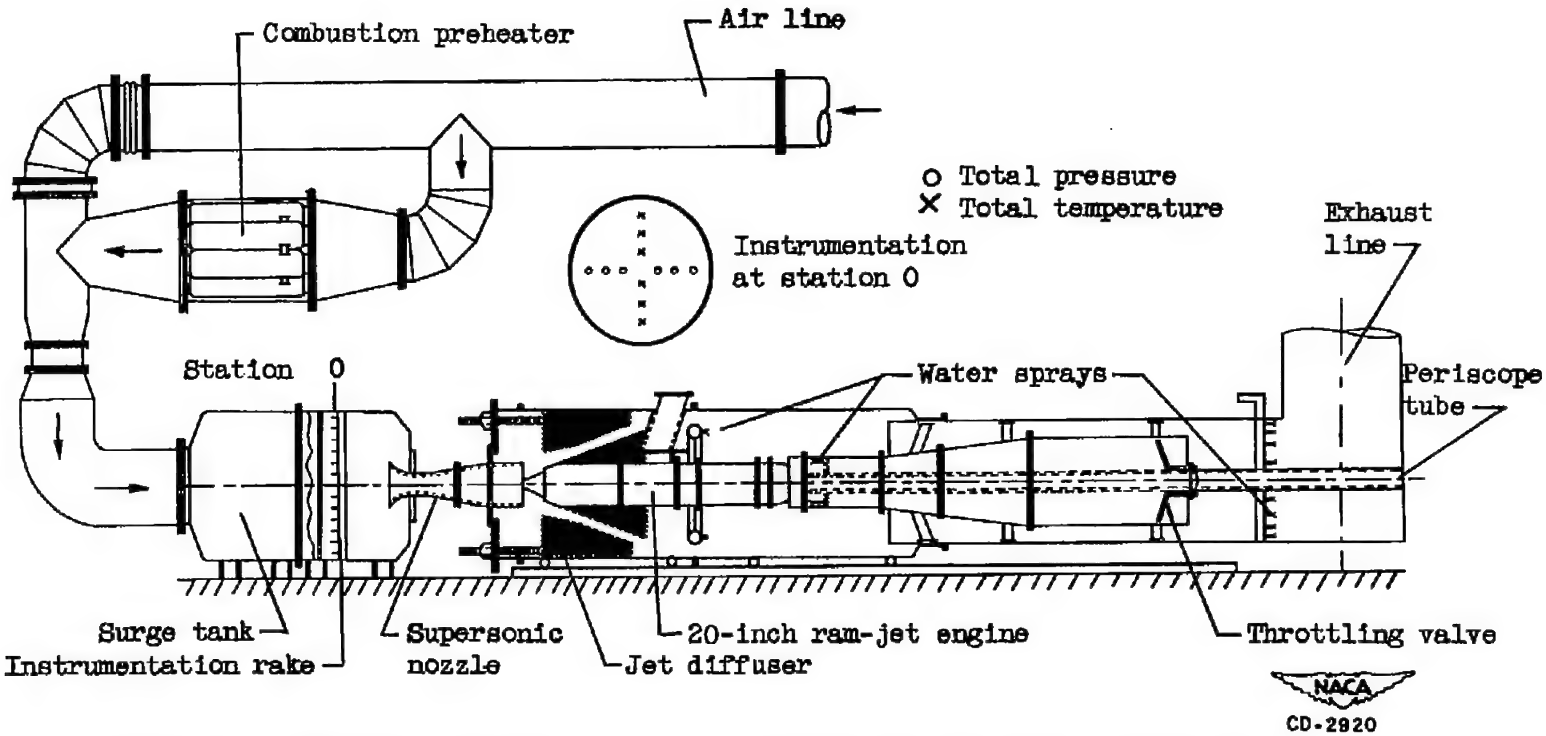

Figure 1. - Schematic diagram of 20-inch-diameter ram-jet engine installed in free-jet test facility.

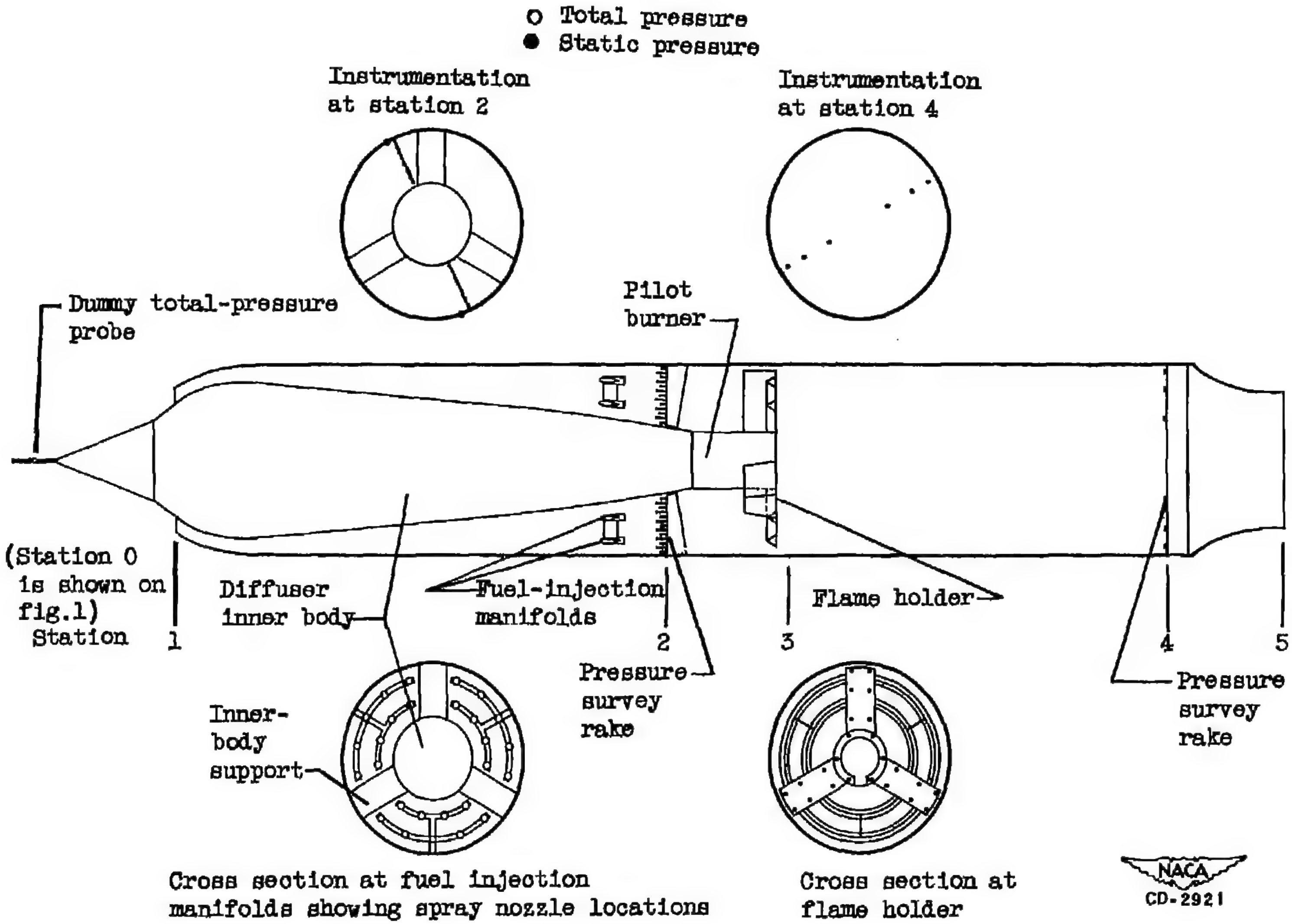

Figure 2. - Schematic diagram of 20-inch-diameter ram-jet engine.

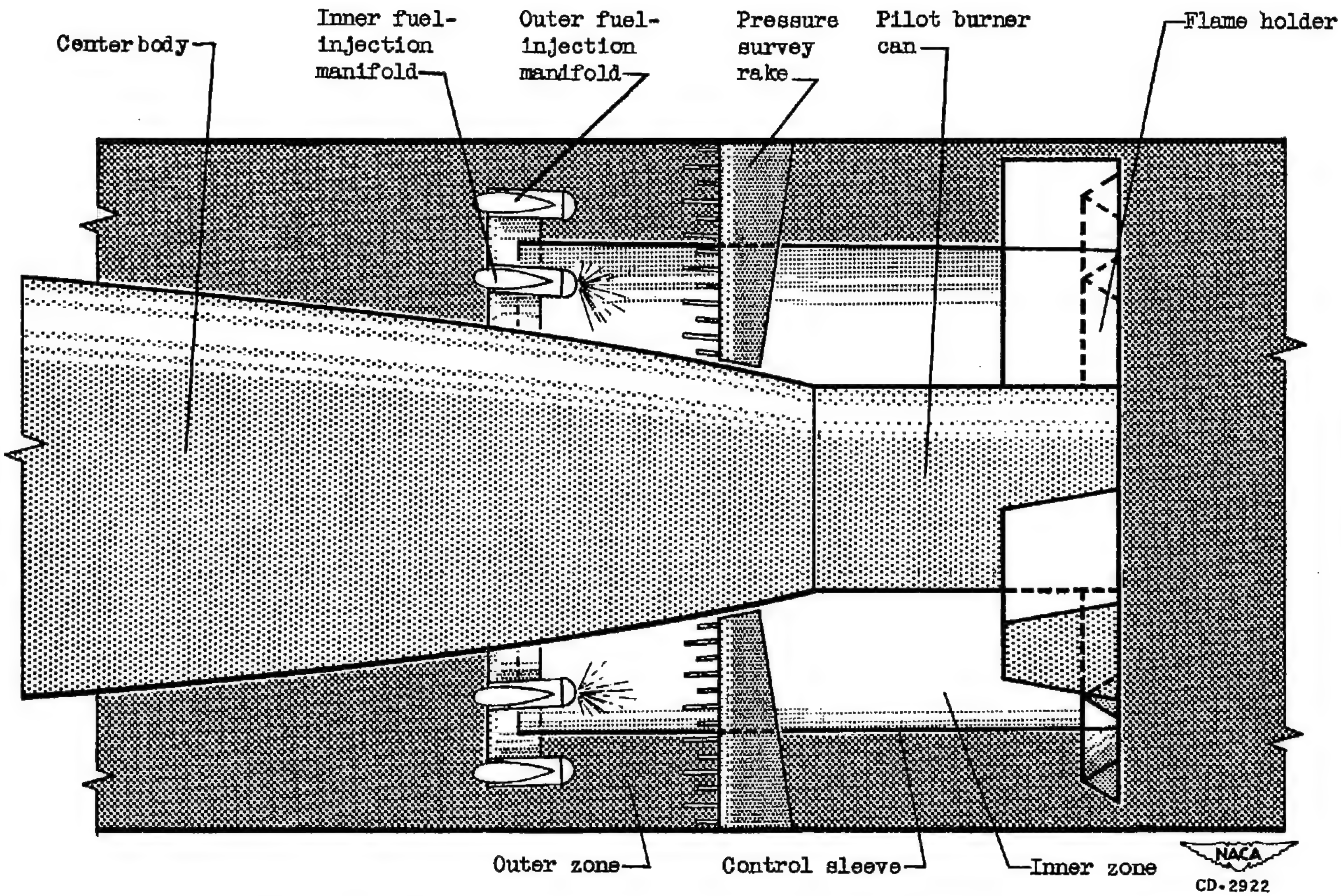

Figure 3. - Schematic diagram showing position of control sleeve.

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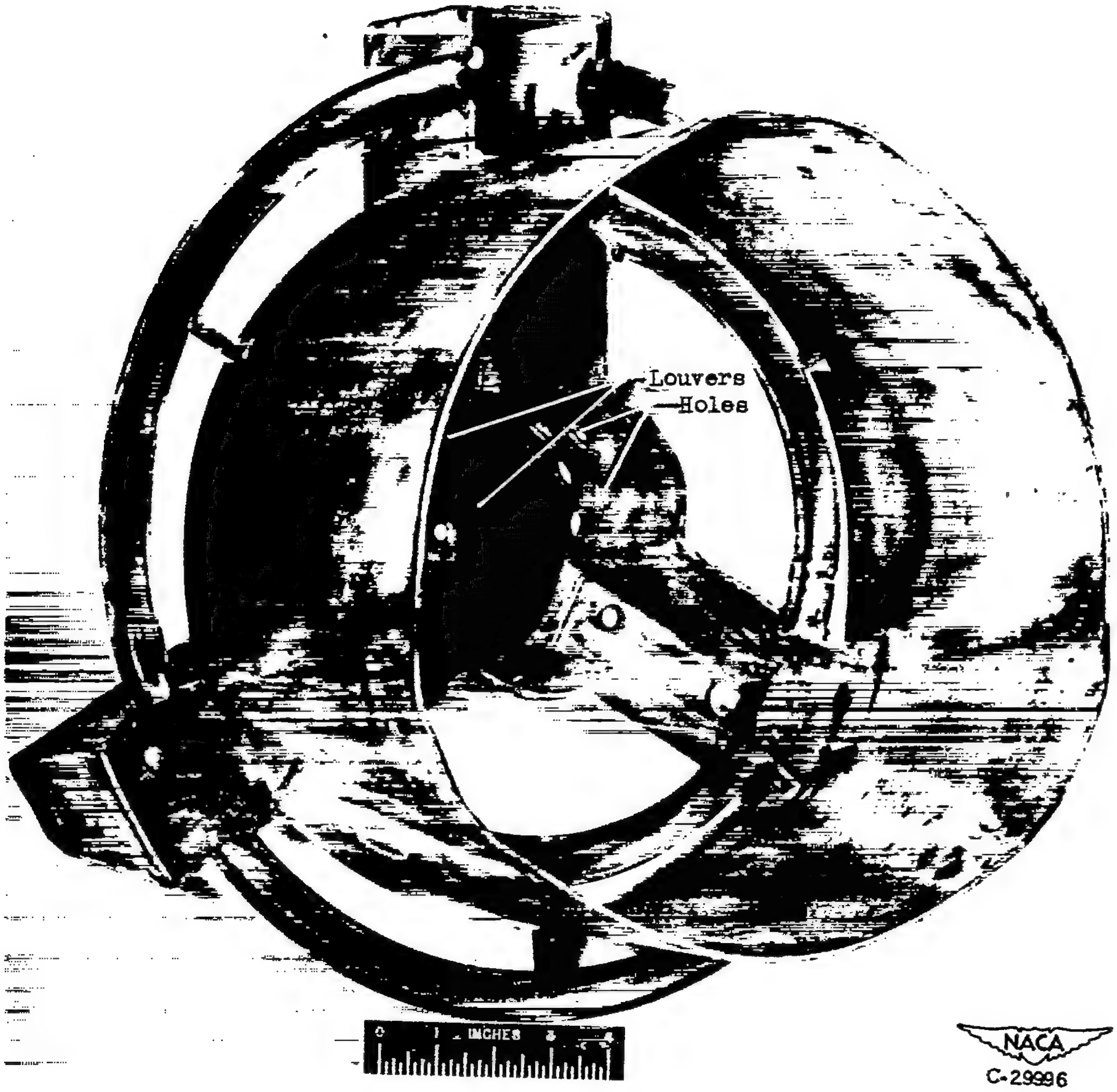
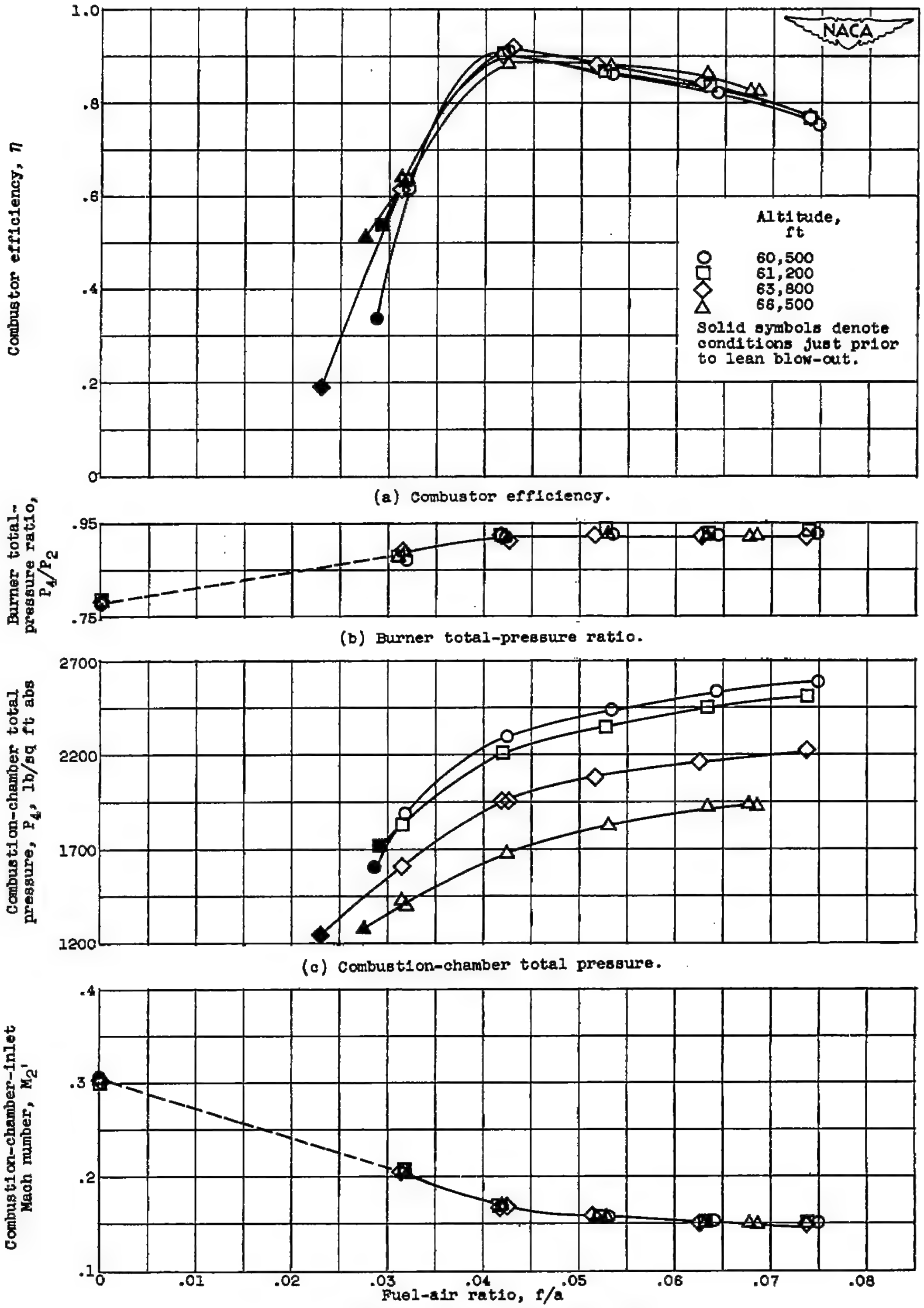


Figure 4. - Photograph of flame holder with control-sleeve extension.



(d) Combustion-chamber-inlet Mach number.

Figure 5. - Performance of configuration 1 (no control sleeve). Flight Mach number, 3.0.

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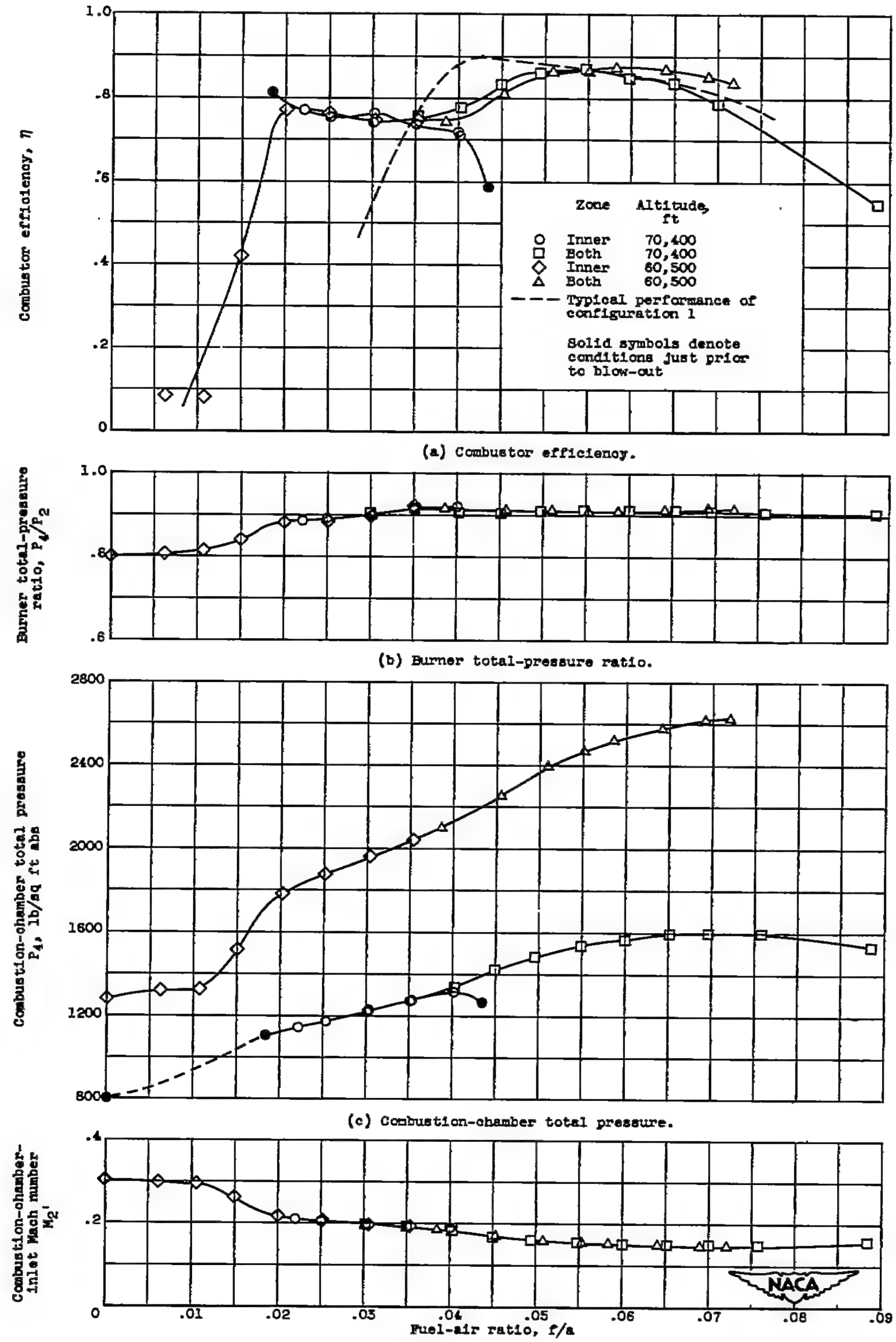

(a) Combustor efficiency.

(b) Burner total-pressure ratio.

(c) Combustion-chamber total pressure.

(d) Combustion-chamber-inlet Mach number.

Figure 6. - Performance of configuration 2 (with control sleeve). Flight Mach number, 3.0.

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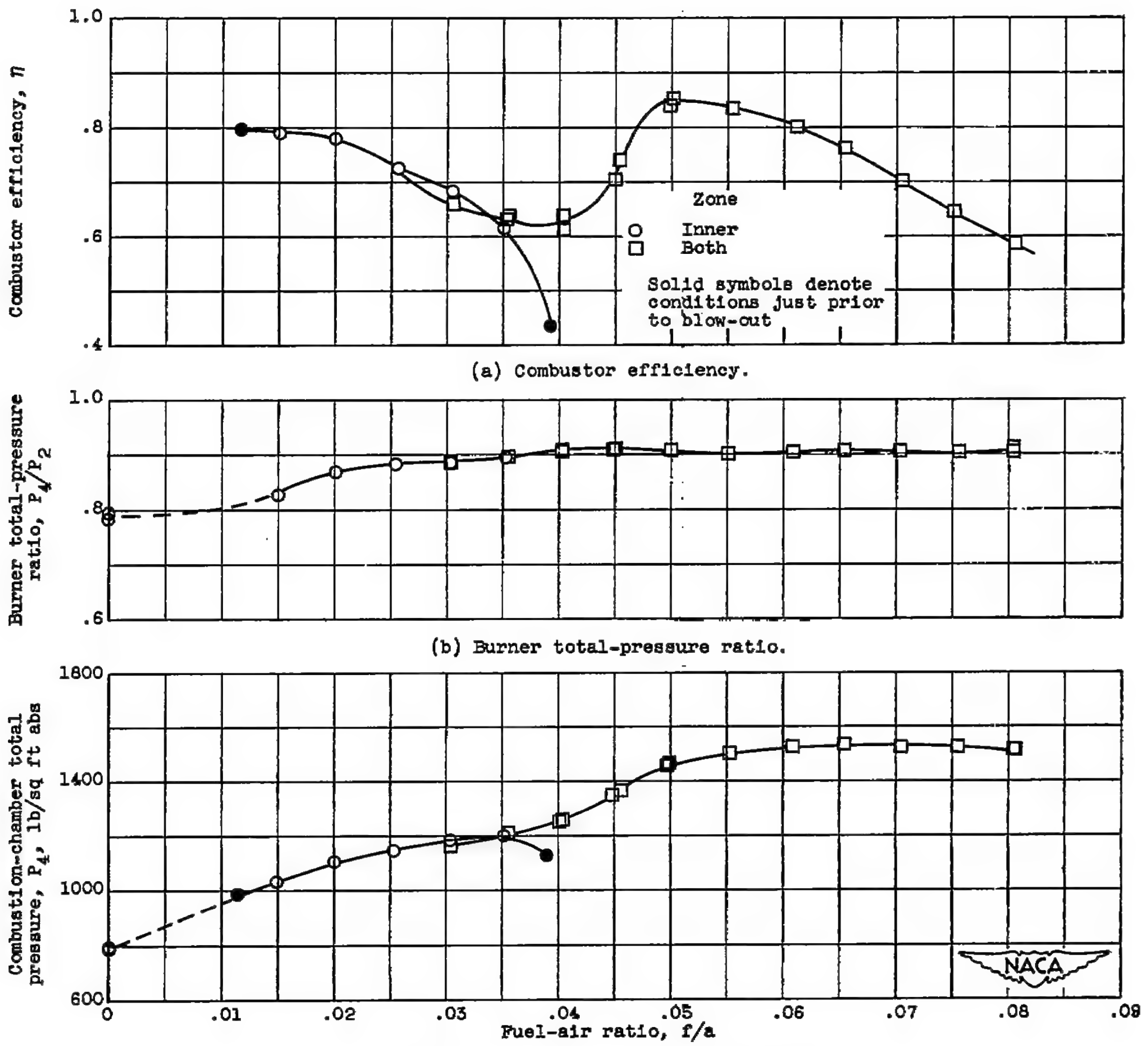
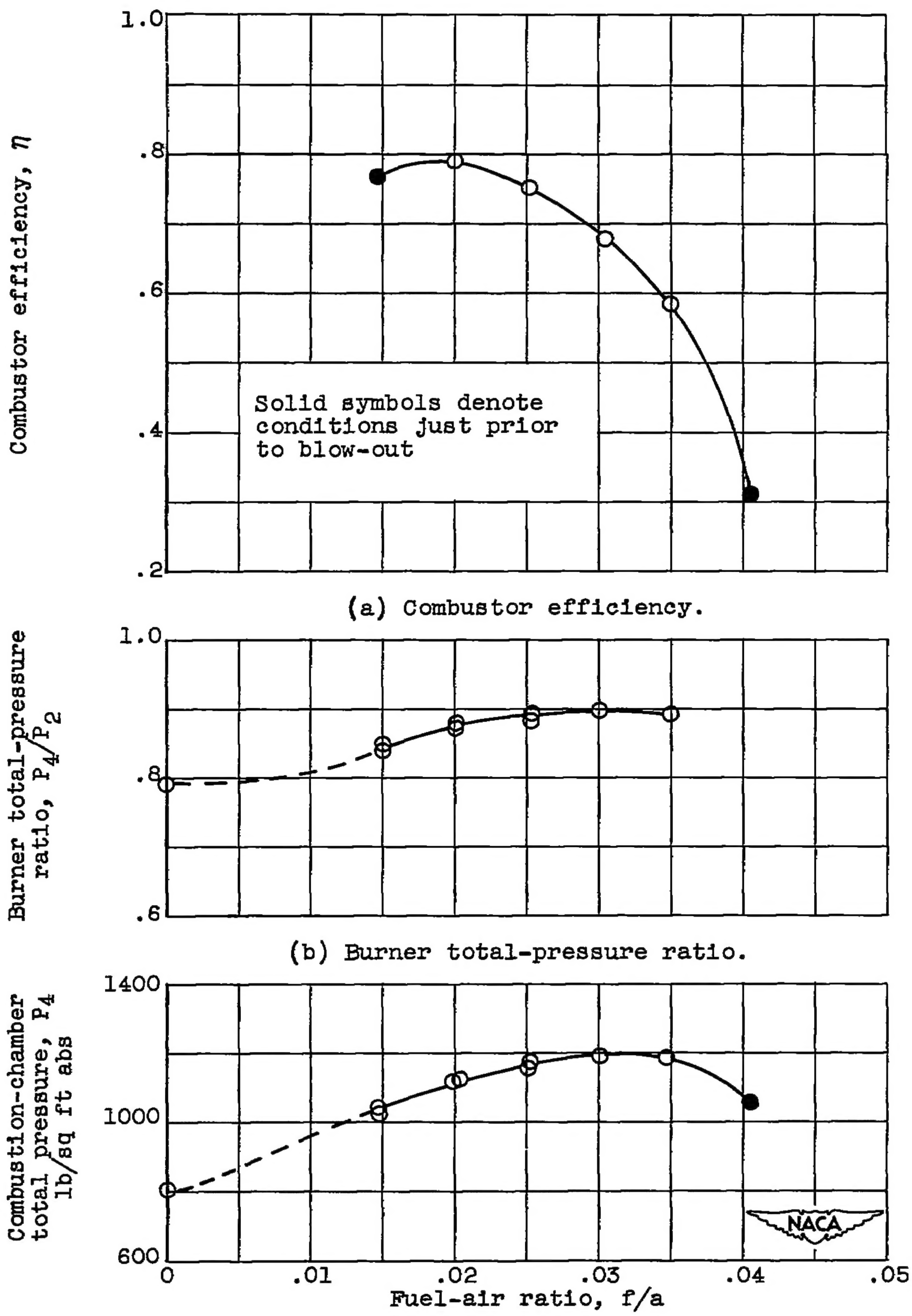
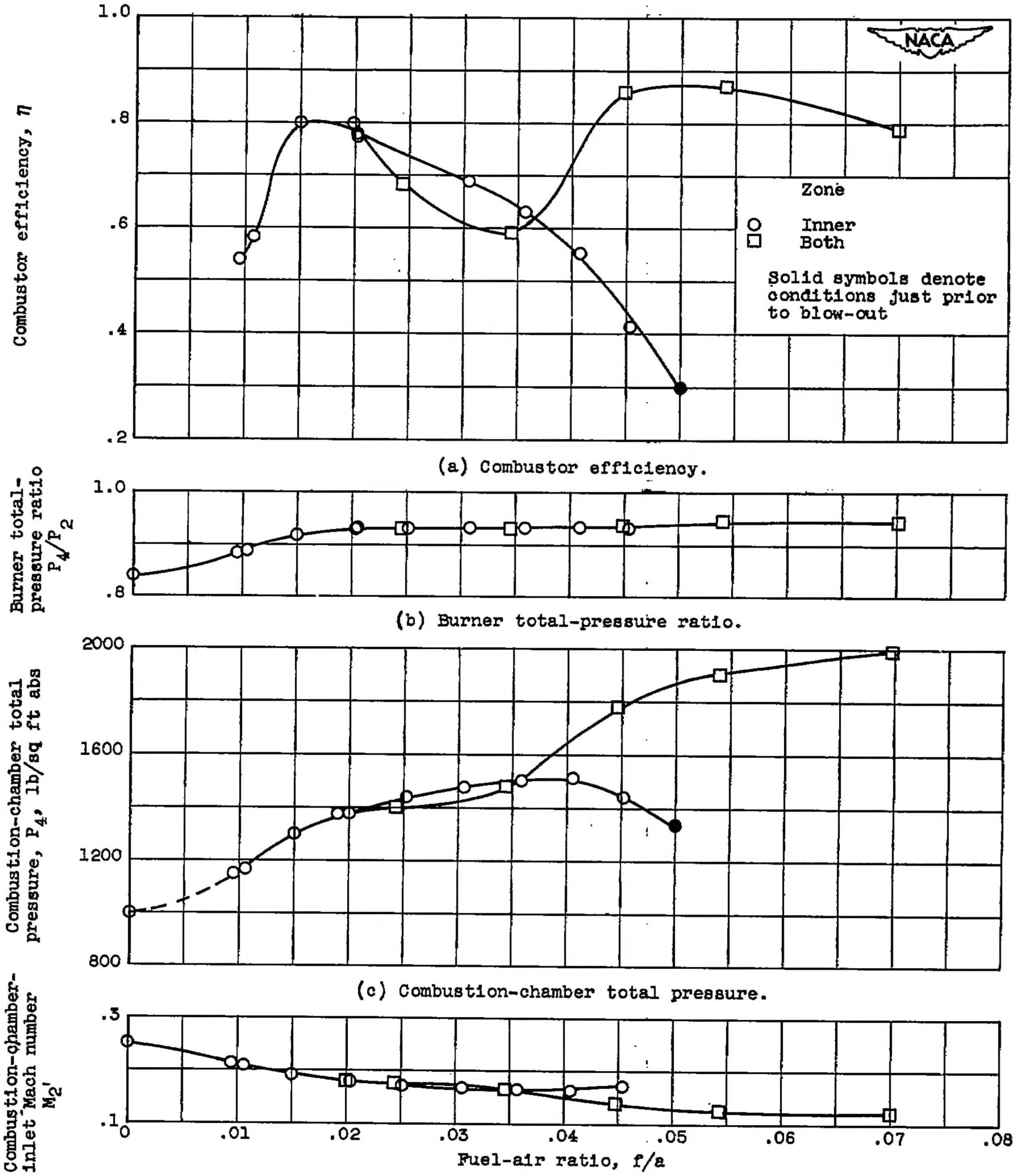


Figure 7. - Performance of configuration 3 (control sleeve extended). Altitude, 70,400 feet; flight Mach number, 3.0.



(c) Combustion-chamber total pressure.

Figure 8. - Performance of configuration 4 (modified pilot burner, inner zone only). Altitude, 70,400 feet; flight Mach number, 3.0.



(a) Combustor efficiency.

(b) Burner total-pressure ratio.

(c) Combustion-chamber total pressure.

(d) Combustion-chamber-inlet Mach number.

Figure 9. - Performance of configuration 5 (45-percent exhaust nozzle). Altitude, 70,400 feet; flight Mach number, 3.0.

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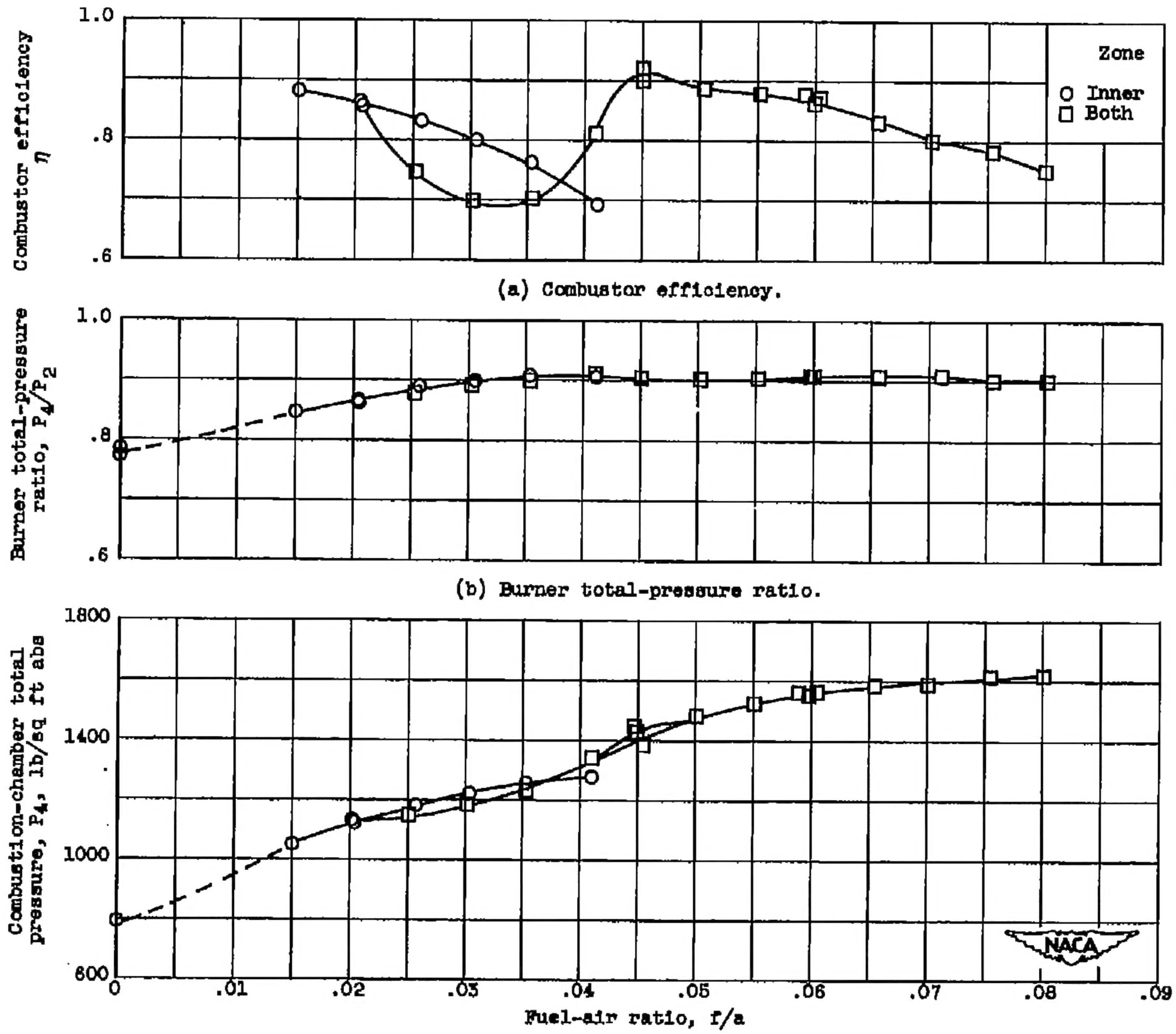

(a) Combustor efficiency.

(b) Burner total-pressure ratio.

(c) Combustion-chamber total pressure.

Figure 10. - Performance of configuration 6 (55-percent nozzle and long combustion chamber). Altitude, 70,400 feet; flight Mach number, 3.0.

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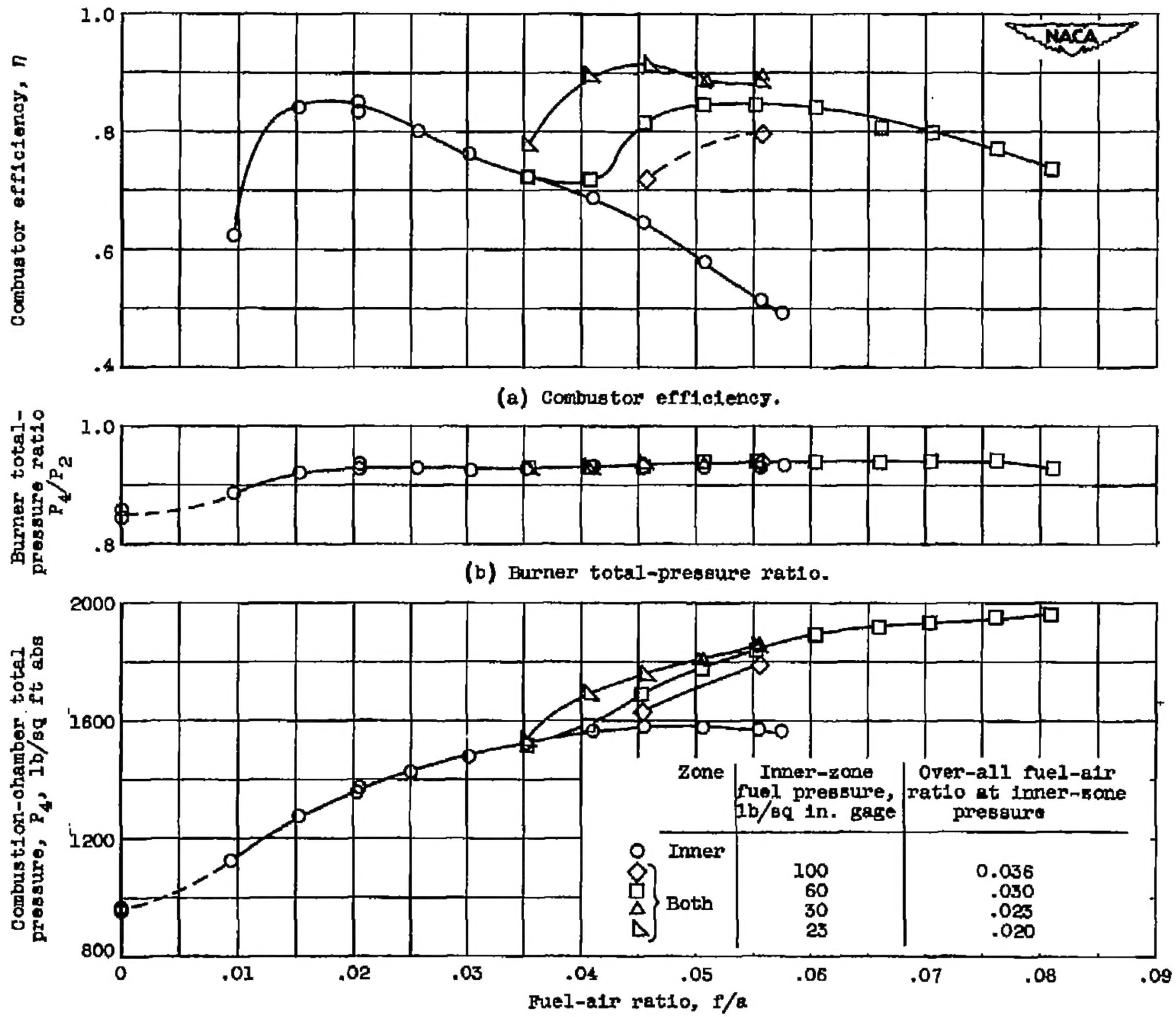

(a) Combustor efficiency.

(b) Burner total-pressure ratio.

(c) Combustion-chamber total pressure.

Figure 11. - Performance of configuration 7 (45-percent nozzle and long combustion chamber). Altitude, 70,400 feet; flight Mach number, 3.0.